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MOISTURE, LIQUID AND TEXTILES A CRITICAL REVIEW (U)

by

Rita M. Crow

*Environmental Protection Section
Protective Sciences Division*

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ABSTRACT

This paper reviews the basic theories of moisture and liquid transport. The methods used to measure liquid-substrate interaction are summarized, compared and discussed as to use. The wetting properties of fibres, yarns, fabrics, chemically-modified fibres and chemically-treated fabrics as determined by many researchers are presented, as well as the results of moisture transfer from fabric layer to fabric layer. Recommendations are proposed for areas where additional research is required on wetting properties to provide a more adequate base for the intelligent design of wicking systems for clothing.

RÉSUMÉ

La présente document porte sur les théories de base du transport de l'humidité et des liquides. Les méthodes utilisées pour mesurer l'interaction liquide-substrat sont résumées, comparées et analysées quant à leur utilisation. Les propriétés mouillantes des fibres, des fils, des tissus, des fibres modifiées chimiquement et des tissus traités chimiquement, telles que déterminées par maints de chercheurs, sont présentées, suivies des résultats sur le transfert d'humidité d'un tissu dans un autre. Certains sujets de recherche sont proposés pour mieux définir les propriétés mouillantes des tissus et donner une base plus adéquate pour assister la conception de systèmes d'imbibition pour les vêtements.

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INTRODUCTION

All clothing involves the interaction of liquid or vapour with a material. In wear, a person gives off perspiration which is removed from the skin through clothing. It is claimed that underwear of low regain fibres facilitates the removal of this perspiration. Specific clothing, such as rainwear or chemical protective clothing, is specially engineered to keep liquids or vapours from reaching the skin. The understanding of the movement of liquid through materials or the repulsion of them by materials is essential to the intelligent design of such clothing. Thus this literature review of the studies done on the movement of liquid in and through textiles was undertaken in order to determine the level of understanding of this subject and the associated knowledge gaps and to recommend areas where additional research is required in order to provide a more adequate base for designing wicking systems for clothing.

In the textile field, there have been three major surges of interest in the interaction of textile materials and liquids. The first was the search for water-repellent materials and finishes, the second the desire to make hydrophobic-synthetic fibres as "comfortable" as natural fibres and the third, to create the ideal super-absorbent for personal or medical use. On the periphery, there has always been the continuing motivation to make textiles more wettable in order to make their dyeing and finishing more efficient.

The first work on liquid-solid-air interactions were of a theoretical nature carried out by physicists such as LaPlace, Young and Washburn who set out the basic equations to explain these interactions. Numerous textbooks have been written, expanding and amending these equations. Next came the theories of how moisture and textiles interact. Starting in the late fifties and carrying over into the eighties were the experiments which consisted of putting various liquids on various fibres, yarns or fabrics or vice versa to study quantitatively their interaction. Because these experiments were quite readily done, researchers tended to get carried away with the number of variables examined. Recently, some workers have tried to correlate experiment with theory. A few have been fairly successful, but the majority have just assigned an equation to fit their results. Finally some work has been done on the transfer of water from fabric layer to fabric layer. This paper will review all these aspects.

THE THEORIES OF MOISTURE AND LIQUID TRANSPORT

WATER VAPOUR SORPTION

When a dry fibre is put into a moist environment, it picks up water and releases heat in doing so, this being more pronounced the more hydrophilic the fibre. The basic shape of the percent regain versus humidity curve is sigmoidal, the more hydrophilic the fibre, the more pronounced this curve is. It is based on these facts that the theories of moisture absorption have been developed.

Pierce in Hearle and Peters (1960) (H&P) postulated that, with cotton, there are two possible forms of adsorbed water, one chemically bound to it and the remainder adsorbed in liquid form. These are named α or reactive sites and β or inactive sites respectively. The β water molecules lie on top of the α water molecules which are chemically attached to the fibre surface. It is largely the β water molecules which contribute to the vapour pressure.

Speakman in Morton and Hearle (1975) (M&H), in his work on wool, divided the water present in a fibrous mass into three phases. The first phase is tightly bound to hydrophilic groups in the side chains of the keratin molecule, the second phase is attached to groups in the main chain and replaces the crosslinks between the molecules and the third phase is more loosely attached and is only appreciable at high humidities. The third phase is equivalent to Pierce's indirectly attached β water. He (H&P) found a linear relationship between the concentration of β water and the rigidity of the wool fibres and said that the slight deviation from linearity above 80% R.H. was due to capillary water. He associated the heat of adsorption with the α water which is considered to combine with the reactive side chains.

Windle's theory (M&H) is the hypothesis that there is localized water directly attached onto absorption sites and limited to one water molecule per site, intermediate water absorbed onto localized water molecules and limited to one on each localized water molecule and then mobile water absorbed onto intermediate water molecules with no restriction on numbers.

Other theories consider the water molecules to be in solution with the fibre molecules or that some water is present as hydrates formed with definite units of the polymer molecule and that the remainder forms an ideal solid solution in the polymer (M&H).

Cassie (1946), in reviewing work by King, says the rate of flow of water vapour increases greatly at 75 to 80% R.H. because the vacant localized sites which deactivate diffusing molecules are now full and so other "deactivating centres" now become important. Presumably their influence is less than that of the localized sites at the rate they deactivate the diffusing molecules. This explanation may account for a statement made earlier in his paper that the differential heat of wetting becomes zero for textiles exposed to saturated air, i.e. there are no more sites for the water to be absorbed onto.

Morton and Hearle (1975) write that it is difficult for the water molecules to penetrate into crystalline areas and for absorption to take place because of the crosslinking there. Thus areas accessible to moisture will be either non-crystalline areas or surfaces of crystalline regions. In a dry structure, there are no water molecules holding the polymer chains apart, so there is more crosslinking. The presence of crosslinks in a dry structure tends to hold the molecules together in the network and makes cross-link formation easier than in a structure with few crosslinks. Thus an initially dry specimen will always retain a higher number of cross-links and less water absorption than an initially wet specimen in the same atmosphere, giving rise to the "peat-moss effect" (Osczevski, 1983).

When a textile material is placed in a moister atmosphere, there are considered to be two waves of diffusion differing in magnitude and speed and related to the diffusion constants involving heat and involving moisture (M&H). After the initial diffusion process, there is a second stage in which swelling stresses relax and so alter the equilibrium moisture condition towards which the diffusion is proceeding. This could explain why the humidity versus swelling curve is also sigmoidal as the humidity regain curve is. Diffusion rates decrease as humidity increases, increase as temperature increases and decrease as the density of packing increases (M&H).

Except at high temperatures and humidities, the regain decreases with temperature (M&H). In the temperature range of 15 to 32°C, Fuzek (1985) found that generally temperature does not effect equilibrium regain for a constant humidity of 65% R.H.. However, increasing the temperature at a constant absolute humidity decreases the percent equilibrium regain.

CONDENSATION OF WATER VAPOUR IN TEXTILES

There has been some discussion as to whether or not liquid water occurs in textiles below saturation vapour pressure. Morton and Hearle (1975) contend that condensation begins in a wedge-shaped part of a fibre to initiate a capillary and that there is a significant amount of capillary water present only at relative humidities greater than 99%. However, Barkas (H&P) theorizes that above 60 to 70% R.H. and 22 °C, capillary water exists and below these conditions, water is held to the textile by molecular forces. To support this view, he considered "a horizontal capillary filled with water and not in contact with any outside source of liquid. In a saturated atmosphere, the liquid surfaces at the end of the capillary will be planar. Reduction of relative humidity will cause slight evaporation, thereby creating a curved meniscus and creating a tension in the liquid in equilibrium with the surrounding relative humidity. Further reduction of the relative humidity will cause evaporation of water until the curvature of the meniscus is equal to the radius of the capillary. The meniscus is then hemispherical and the slightest further reduction will cause the liquid to evaporate and the meniscus to retract into the tube. Hence, at any given relative humidity, all the capillaries with a radius less than a given value will be filled with water and all those with a radius greater than this will be empty." Hearle and Peters note that the term 'curvature of meniscus' ceases to be meaningful when the dimensions of the capillaries in which the meniscus lies are of the same order of size as molecular dimensions (10^{-9} cm). They show theoretically that this occurs when the relative humidity lies below 60 to 70 percent at 22°C. They conclude that below this limit all the water must be held by molecular forces.

WETTING OF TEXTILES WITH A LIQUID DROP

Baxter and Cassie's (1945) explanation of the wetting process has stood over the years and thus is summarized here. (Only the more classic equations involving the wetting of textiles will be presented here.)

When water drops freely, it forms a spherical shape rather than a cylindrical one because the sphere has the minimal surface area to contain the water. In order to increase the surface area of water by 1 cm², work of about 7.5 µJ must be done on it. Conversely, the tendency of the surface to contract is measured by the energy required to form the surface and is known as surface energy or tension of the liquid.

All systems come to equilibrium with the minimum possible potential energy. Thus, when water is dropped onto a clean glass surface, it spreads because the glass molecules hold the water molecules more firmly than the water molecules hold each other. Paraffin wax does not hold water molecules as powerfully as water does and work must be done on the system to make a paraffin-water interface. Water will form itself into a drop on the paraffin to give the state of minimum energy. Surfaces which behave as paraffin wax does are known as water-repellent surfaces, but the apparent repellency of the surface is due to the surface energy of the water rather than to any repulsive force exerted by the paraffin surface.

Three surfaces or interfaces are involved in the contact of water with a solid, and the behaviour of the water is determined by the energy per unit area of the interfaces. These energies are γ_{LA} for the water-air interface, γ_{SA} for the solid-air interface and γ_{LS} for the liquid-solid interface. When a drop is placed on the solid, it will continue to spread over the surface as long as the energy of the system is decreasing or as long as

$$\begin{aligned} &\gamma_{SA} > \gamma_{LA} + \gamma_{LS} \\ \text{or} \quad &(\gamma_{SA} - \gamma_{LS}) > \gamma_{LA} \end{aligned}$$

When $(\gamma_{SA} - \gamma_{LS})$ is equal or less than γ_{LA} , the drop ceases to spread and the edge of the drop comes to rest on the solid surface, making a finite angle with it. When water comes to rest on a solid surface, it makes a contact angle θ with it. Because this is an equilibrium position, the potential energy of the system must be minimum and any displacement of the surface will give no change in energy of the system. The equation to describe this is the classical Young equation

$$\begin{aligned} &\gamma_{SA} = \gamma_{LS} + \gamma_{LA} \cos \theta \\ \text{or} \quad &\cos \theta = (\gamma_{SA} - \gamma_{LS}) / \gamma_{LA} \end{aligned}$$

This condition is maintained until $(\gamma_{SA} - \gamma_{LS})$ becomes equal to $-\gamma_{LA}$ or until the contact angle is 180° . This is when water has formed a spherical drop with minimum surface consistent with its volume. Thus, the three different types of behaviour of water on a solid surface are:

Region I. $(\gamma_{SA} - \gamma_{LS}) > \gamma_{LA}$, the drop spreads right out.

Region II. $\gamma_{LA} > (\gamma_{SA} - \gamma_{LS}) > -\gamma_{LA}$, a non-spherical drop with a finite contact angle is formed

Region III. $(\gamma_{SA} - \gamma_{LS}) < -\gamma_{LA}$, a completely spherical drop is formed.

Young's equation has been modified in various ways to include a receding or advancing contact angle, a rough or porous surface or a wet or dry surface (Moillet, 1963).

Cassie and Baxter (1944) considered that parallel cylinders correspond to textile yarns and when a liquid is placed on them, there are two surface areas, an area f_s of solid-liquid interface and an area f_a of liquid-air interface such that

$$f_s = \frac{\pi r}{r + d} (1 - \theta_A / \pi)$$

and

$$f_a = 1 - \frac{r}{r + d} \sin \theta_A$$

where r = radius of the cylinders

$2d$ = the distance between them

θ_A = the contact angle between the solid and liquid.

Cassie and Baxter went on to assume that fibres in yarns lie in a hexagonal pattern, again at a distance of $2(r + d)$ between their centres. Experimentally, they found that large apparent contact angles (i.e. poor wettability) are achieved when $(r + d)/r$ is large, but not large enough to let raindrops through. They say this is obtained in clothing by using fibres of a small radius, so that the ratio $(r + d)/r$ is large without the presence of large pores. They measured this ratio for duck feathers and found it to be ideal. Finally they say that for water resistance, there cannot be a lot of fibres on the surface which would be free to move under tension and be pulled together by rain drops (as wet dog-hair is), as this decreases $(r + d)/r$ and the contact angle.

Kawase et al (1987) have attempted to extend Cassie and Baxter's equations to include wax-coated mesh screens and found the calculated and observed results to be of the same magnitude.

MOVEMENT OF WATER IN TEXTILES

Laplace's classic equation for penetration of a liquid into a cylindrical tube or a capillary is given

$$\Delta P = \frac{2\gamma \cos \theta}{r'}$$

where ΔP is effective pressure difference between the two phases and r' is the radius of the tube.

Washburn's equation (1921) for liquid flow in a horizontal capillary is

$$l^2 = \frac{\gamma \cos \theta}{\eta} \frac{r'^2}{2} t$$

where l is the length of the column of liquid at time t
 η is the viscosity of the liquid
 r' is the radius of the capillary
 θ is the contact angle.

This equation reduces to

$$l = k \cdot t^{1/2}$$

where k is a constant which describes the "system".

Finally, Poiseuille's law considers volumetric flow, such that

$$dV/dt = \frac{\pi r^4}{8\eta s} \Delta P$$

where dV/dt is the volume rate at which a liquid moves through a porous channel.

Gillespie (1958,1959) and Schwartz and Minor (1959A, 1959B) examined the theoretical spread of liquids, both the spread from a drop and up a capillary. The former verified his theory with experimental results. Kissa (1981) and Kawase et al (1986) have examined the capillary spread in textiles, but this work has been mainly the finding of numerical values for a number of constants.

Since most textile fabrics do not approximate flat surfaces or have ideal capillaries, attempts to apply the classic theories of liquid-solid interaction to textiles may be somewhat futile. Instead, finding the reason why textiles deviate from these theories would be more productive.

REVIEW OF METHODS TO MEASURE LIQUID SUBSTRATE INTERACTION

Harnett and Mehta (1984) define wickability as the ability to sustain capillary flow and wettability as describing the initial behaviour of a fabric, yarn or fiber when brought into contact with a liquid, i.e. prior to wicking taking place. Skinkle (1949) uses the terms absorbability and wetting-out, the former being defined as the ability of a fabric to take up water and the latter as the ability of a liquid to enter a fabric and to displace the air from the capillary spaces. He says that both terms refer to the same phenomenon but absorbability refers to the fabric and wetting-out to the liquid. Kissa (1981) gives three modes of wetting, total immersion of the substrate, sorption of a liquid from an unlimited reservoir and sorption of a limited quantity of liquid, i.e. a drop. Test methods have been developed to simulate these various interactions of the liquid and the substrate. As will be discussed later, the end use of the substrate will determine which method is used. The various tests will now be reviewed and their use discussed.

DROP PENETRATION RATE

The standard test used is the AATCC Test Method, 39-1977. (Bertoniere (1985), Harper (1976), Zeronian (1986)). Here a drop of known size is dropped onto a fabric and the time for the drop to penetrate the fabric determined. De Boer (1980) comments that if the time for the drop to disappear in the AATCC drop test is longer than 1 min, then the results are dubious. There are slight variations to this method. Kawase (1986) put liquid in bottom of a desiccator, mounted the fabric to be tested in embroidery hoop and put it in the desiccator for 2 hours. He then put a measured amount of liquid on the fabric surface with a micropipette and

recorded the spreading of the drop with a video camera. He cut out the photographed drops from the film at various stages of wetting and determined their size by weighing them and comparing these weights with calibrated ones. Kissa (1981) did much the same thing except he photographed the drop spreading and measured the area on the photographs, using a stain in the liquid. Bogaty (1953) measured drop absorption by placing 0.2 ml of water on the fabric surface and recording the time for complete disappearance of liquid. To measure spreading of liquids, he applied the liquid to the fabric held in a hoop. The liquid was allowed to spread for 10 minutes and the area covered by liquid was marked, allowed to dry, and then cut out.

VERTICAL WICKING

There are two versions of this, either the measurement of time required for the liquid to rise a set distance or the measurement of the distance the liquid rises in a set time. Bogaty (1953) measured vertical wicking using a 2.54 cm (1") wide vertical strip and recording the time for water to rise 2.54 cm (1"). Bhargava (1985) used coloured distilled water and measured the height of wicking after 1, 2 and 5 sec. Bertoniere (1985) determined the vertical wicking by measuring the distance travelled by a front in 15 minutes up a 25x2 cm fabric strip immersed a depth of 2 cm in the liquid. Harper (1976) measured the time of wicking vertically 3 cm, and measured liquid transport by sewing a 4x1" strip to center of 6x6" swatch of fabric which was then put over the top of a beaker containing the liquid. Zeronian (1986) measured the rise of liquid after 10 minutes. De Boer (1980) marked lines on the fabric strip every $\frac{1}{2}$ cm with water-soluble ink and timed the rate of wicking up the strip.

WATER ABSORBENCY

Bhargava (1985) measured water absorbency by measuring the time it took a fabric to sink in distilled water and then centrifuging the wet fabric, weighing it and expressing the amount of water absorbed in it as a percent of dry weight. Similarly, Bogaty (1953) measured imbibition by soaking the fabric, centrifuging it and weighing it. Morton and Hearle (1975) claim that suction is better than centrifuging since the force tending to remove the water is independent of the amount of water in the

capillary spaces of the material. This is not the case with centrifuging. De Boer's immersion test (1980) was to wet out the sample, remove it under controlled conditions and weigh it. Madan (1978) carried out a semi-water absorbency test by weighing the fabric before and after vertical wicking. Somewhat akin to the water absorbency tests is the saturation value test which de Boer measured by putting a drop on fabric, then after 10 min, cutting out the spot and weighing it.

CRITICAL SURFACE TENSION

Ward (1985) used a sink-float technique on the principle that when the critical surface tension (CST) of a fibre is greater than the surface tension of a liquid, the fibre will be completely wetted and sink. This is the point at which liquids have a zero contact angle and therefore the point at which the liquid spreads spontaneously. Because of hydrogen bonding (H-bonding) between liquid and solid, H-bonding liquids generally do not give the same CST as non H-bonding liquids. Bateup (1976) measured the critical surface tension of wool using the sink-float method and snippets. In a related type of test, Schuyten (1949) ran drops of liquids of various surface tensions down inclined strips of fabric and detected electrically when the tail of the drop penetrated the fabric.

CONTACT ANGLE

Penn (1981) measured the advancing and receding wetting forces by the Wilhemy balance principle. He used 4 liquids of known surface tensions which were arbitrarily broken down into polar and nonpolar physical interactions between molecules. Pirie and Gregory (1973) dropped the liquid onto a solid between the light and lens of a projector. The light was shone onto a piece of photographic paper just long enough to expose it, and thus record the shape of the drop on the solid.

OTHER TESTS

For specialized information, other methods are invented. For instance, Miller and Clark (1978) looked at flow-through properties of a fabric for which they made an apparatus in which a known flow is imposed and pressure changes during contact are determined.

COMPARISON OF TEST METHODS

Harnett and Mehta (1984) carried out a survey and comparison of laboratory test methods for measuring wicking. They found that the spot test gave results consistent with the strip test and the plate and syphon tests had similar rates of wicking for all but polypropylene, wool and PVC. They found a lack of correlation between wettability and wickability. They concluded that the strip test which represents the rate of liquid movement gives good correlation between height wicked and % moisture. For the spot test, there was a weak correlation between time to disappear into fabric and rate of increase in radius, showing that wickability and wettability are not strongly related. The syphon measures a parameter of wicking behaviour virtually unrelated to those of the other tests. There was a high correlation between wicking and rate of increase of radius, suggesting that the strip and the spot test give equivalent measurements of wickability. In the spot test, low correlation between mass transfer and rate of increase of radius or wicking suggested that transverse wicking behaviour of textile materials is only loosely related to longitudinal or areal wicking behaviour. It was considered that the spot test is a better simulation of real wear conditions than other tests. Wicking behaviour perpendicular to the fabric plane cannot be reliably inferred from planar wicking and an independent test method such as the plate test is required for its determination.

They found inaccuracies from all tests when materials used were slow to wet or wick. They also found several examples of inconsistency between results obtained by different test methods, particularly changes in wicking behaviour after aqueous scouring. They found very little difference in wicking behaviour carried out at 35°C and 20°C.

SELECTION OF METHOD

WATER-REPELLENCY

The tests for water-repellency can be divided into two categories, those which give information on the resistance of the fabric to the

penetration by rain and those which give information on the resistance of the fabric to surface wetting or penetration into but not through the fabric. The former include the Drop and Drop Penetration Test, the Impact Penetration Test, the Hydrostatic Head and the Rain Test. The latter are the Spray Test, the Static and Dynamic Immersion Test and the Wetting Time Test. The Bundesmann Test gives a figure for both in one test. Details of these tests are given in Moilliet (1963).

ABSORBENCY

The two factors important in absorbency are the total amount of liquid absorbed and the rate of absorption of the liquid. Thus, absorbency can be measured by the amount of liquid absorbed on immersion or from a wet surface, the absorption time of a drop, the sinking time of a fiber or yarn or patch of cloth and by capillary travel by wicking vertically or horizontally. However, as of 1985, Chatterjee pointed out that nobody had yet invented a single, simple test which could be used to objectively evaluate "absorbency", either as a practical performance measure of a material or as a scientific phenomenon.

COMFORT

The tests for measuring comfort have been water-vapour transmission and/or heat loss using a heated, sweating hot plate. However, since water-vapour transmission is mainly a function of fabric construction rather than fibre type and since sweating is considered to involve the wicking which is not specially accounted for with the sweating hot plate, other tests were used to compare the "comfort" of materials.

As outlined by Renbourn (1972), there are three major forms of moisture transport in clothing. First, for a person to be comfortable it is necessary for insensible water vapour to pass from the skin through the clothing. Thus, water vapour transmission of clothing is desirable for comfort. Second, when one starts to work hard, sweat is produced faster than evaporation can occur at the skin and passes through clothing. In this instance, if the clothing is in contact with the skin, it will blot up this moisture. The amount of moisture the fabric can hold and how quickly

moisture can pass to the next layer or evaporate into the air, if there is only one layer, are pertinent to cooling and comfort. Finally, there is the phenomenon of water movement in clothing when condensation of sweat occurs within the clothing under cold conditions and it subsequently wicks back to the body to produce an evaporation-condensation-wicking cycle. This would only occur in extreme cases of work load and low temperatures.

Renbourne goes on to suggest that normally, entry of water into the interstices of a fabric is by wicking, i.e. capillary action, aided in clothing by the gentle bellows effect of breathing and of body movement. He says that some pumping effect is seen at the chest, back and shoulders but it is most marked at the feet, particularly with the high pressure produced during walking. He suggests that such transfer of liquid from one fabric to another is thus caused by pressure and friction and may be regarded as a sort of blotting effect. He says that it is somewhat doubtful whether conventional textile laboratory tests of wicking properties throw a great deal of light upon the mechanism of sweat wicking through the inner garments and that only direct experimentation will throw light upon how wicking takes place by gravity, against gravity or through the thickness of a fabric.

WETTING PROPERTIES

FIBRES

To differentiate between unwashed and washed cotton fibres, Ward and Benerito (1985) measured contact angles and used the sink-float technique to determine surface tensions. They found that the contact angles decreased after washing. This was expected since the cleaner the surface, the more readily a liquid spreads and wets the surface. They found that all fibres floated at surface tensions of liquids above 60.1 mN/m, the washed fibres sunk in liquids with surface tensions of 56.5 or less and the unwashed ones sank in liquids with surface tensions of 47.5 mN/m or less.

Penn et al (1981) examined the effects of drawing on the wettability of polyethylene terephthalate filaments. They measured the advancing and receding wetting forces of filaments using 4 liquids of known surface tensions. Drawing made the fibers less wettable for all four liquids, one of which was non-polar and three, polar or H-bonding types.

They calculated an estimate of the surface energies of the filaments for a draw ratio of 1.0 and 4.0 and found them to be similar. They concluded that the method used to estimate surface energies was invalid since the wettability of the filaments decreased with drawing and that another means of surface analysis would have to be found.

Bateup et al (1976) studied the wettability of wool fibres. They measured critical surface tension (CST) of wool using the sink-float method, snippets and non-polar organic liquids. They found the CST of wool to be about 30 mN/m in air at 60% RH. Removing the grease from the wool's surface with methylene chloride did not affect the results which were similar to polyethylene (31 mN/m). They concluded that the lipid material is tenaciously held on the surface of the fibers and can't be removed with methylene chloride. Efficient cleaning by Soxhlet extraction with benzene, ethanol and water raised the CST to 37 mN/m which they considered to be characteristic for wool peptide material and of peptide materials in general.

When they measured the CST of unmodified wool fibers with aqueous solutions of nonionic surfactants, they found that at concentrations greater than the critical micelle concentration, the solutions acted like nonpolar liquids and gave CST values similar to those obtained with nonpolar organic liquids. They concluded that surfactant molecules do not undergo reorientation when the surfactant solution is contacted with low-energy wool fibers.

They report that the CST decreases with increasing RH for keratin fibers, but didn't find this had any effect when they placed the wool fibres snippets on aqueous solutions. However, when they placed fibres in a butanol/water mixture, they obtained a CST of 26-27 mN/m for unmodified wool. They thought that this suggested that butanol vapor is readily adsorbed on wool fibers with a consequent lowering of the CST and confirms work of several people who have found that aliphatic alcohols are readily adsorbed by low-energy substrates. Thus, they concluded that nonpolar organic liquids rather than alcohol solutions should be used to predict the wettability of fibers.

Lennox-Kerr (1981) reported on a super-absorbent acrylic for which it is claimed that a combination of absorption and capillary action plays a major part in water transmission through it. It has a microporous structure with thin capillaries in the structure of the fibre. The pores allow it to absorb a considerable amount of liquid and retain it within the structure without being damp to the touch. It wicks from a full beaker of water into an empty one faster than conventional acrylic and its vertical wicking is about the same as a cotton fabric. In hydro-extraction, the super-absorbent acrylic held more water than conventional acrylic. However, the regain of both types of acrylic is the same, about 1%.

Summary

Washing cotton fibres lowers their contact angles and increases their surface tensions. Drawing polyester filaments makes them less wettable. Cleaning wool fibres increases their critical surface tension. The creation of thin capillaries in the structure of the fibre increase its wet properties.

CHEMICALLY-MODIFIED FIBRES

Wallenberger (1978) examined the effect of absorbed water on the properties of cotton and fibers made from hydrophilic polyester block copolymers. In his introduction, he says that below 10% RH, all fibres have a rapid 2-3% moisture regain due to a hydrate formation when there is a direct combination of water molecules with polymer molecules. Above 70% RH, there is an increase in regain due to a looser bonding by van der Waal's forces, leading to a solution of water in the fiber. He made some hydrophobic polyethylene terephthalate (PET) / hydrophilic (water-soluble) polyethyleneoxide (PEO) block polymers containing varying amounts of PEO. He measured their % regains at various RH's and found them to be extremely hydrophilic above 80% RH as are the natural fibers, but hydrophobic below that RH. He found that a small number of long segments rather than a large number of small segments were more effective in increasing regain over 70% RH.

Lofquist et al (1985) added or grafted a hydrophilic copolymer to nylon. In both cases, the regain of the nylon went from about 6% to 13%, as measured at 33°C, 96% R.H. The wickability of the block copolymer was much faster than the nylon and similar to a 40/60 polyester/cotton blend.

Summary

Adding a hydrophilic finish, block copolymer or graft copolymer increases the regain and wickability of a hydrophobic fibre to a level similar to that of cotton.

CHEMICALLY-TREATED FABRICS

Liggett et al (1968) treated a 100% cotton fabric with various chemicals in order to improve, among other properties, the moisture regain. They did find that the addition of hydrophilic materials increased the % regain, from 6.7 to about 8. They say that the hydrophilic materials inhibit the hollow fiber's collapse at the time of curing and that reactants which contain hydrophilic groups presumably form hydrophilic derivatives with the cellulose.

Madan et al (1978) treated cotton with various crosslinking agents and softeners. They found the decreasing order of % regain to be untreated cotton (highest regain), cotton treated with crosslinking agent, cotton with crosslinking plus a softener, nylon, polyester/cotton and polyester. The decreasing order of rate of wicking was cotton with crosslinking (fastest), untreated cotton, polyester, polyester/cotton, nylon and cotton with crosslinking and softener. The decreasing order of % water absorbed was untreated cotton (highest absorbency), the cotton with crosslinking, polyester/cotton, cotton with a crosslinking plus a softener, polyester and nylon.

They explained that water rises in the capillaries in the fibres and yarns of fabrics. The capillary-rise phenomenon depends on the porosity of fiber and interaction of water molecules with the molecular structure in fiber. The rises due to porosity and to molecular structure they call "capillary hydrophilicity" and "intrinsic hydrophilicity" respectively. Intrinsic hydrophilicity tends to retard the rate of rise in the capillary. Thus, water rises in untreated cotton slowly as it interacts with the OH groups of cellulose through H bonding. This takes longer. In treated cotton, the OH groups are crosslinked and so can't slow down the rate at which the water rises in the fabric. In what appears to be a contradiction, they say that the fibres with water-repellent finishes are very slow to wick because their fibre surface is less accessible to water.

Bertoniere and Rowland (1985) studied the spreading and imbibition of durable press reagent solutions in cotton-containing fabrics. They used two series of fabrics. The first series consisted of 4 plain-weave fabrics woven from 12/1 combed cotton yarn with a 3.95 twist multiplier. The same yarn was used in the warp and weft. The warp yarn-count was 30 per inch and the weft varied at 20,30,40,50 per inch. The second series was an intimate blend of cotton/polyester sheetings in which the polyester content was systematically varied to give the following: 0/100, 35/65, 50/50, 65/35, 85/15, 100/0.

They carried out the drop absorbancy test, vertical wicking, drop spread or saturation value and total absorption or imbibition tests. They found that, for the drop absorbency test, the all-cottons were highly

absorbent to water and several durable press reagent solutions. The higher the weft count, the faster the absorbency time relative to the all-cottons. The cotton/polyester sheetings were almost water-resistant, this resistance increasing with the inclusion of DMDHEU (a cross-linking agent) and decreasing when a wetting agent was added.

The results of the vertical wicking tests showed that in the all-cottons, the distance travelled up the wick in weft direction was 1.1 times greater than warp and for the cotton/polyester blends, it was 0.9 times greater, giving an ellipse in weft direction for cotton, and ellipse in warp for the blends. The wicking distance increased with weft yarn count. Wicking was about two times higher in cotton than in the blends series, this including its 100% cotton. Adding wetting agent increased wicking in blends and both series had reduced wicking distance with DMDHEU.

The saturation value decreased with increased weft count and increasing cotton in the blends with most of the treatments. The solution of imbibition, a measure of the solution-holding capacities of the fibres in the fabrics, increased with increasing cotton content and was not affected by thread count.

Zeronian et al (1986) looked at the wetting of polyester and cotton fabrics with a nonionic surfactant solution (TNP). The polyester fabric was type 54 and had a mass of 127g/m² and a count of 24.5x21.2 threads/cm. The 100% cotton had a mass of 100 g/m² and a count of 28.6x31.6. Both fabrics were from Testfabric Inc. They also included Mylar D film in their study. They treated the polyester fabric with a nonionic polymeric hydrophile (NPH). They determined the surface tension of the film with NPH and the vertical wicking, drop absorbency, water retention and solution retention values of the fabrics.

As the concentration of TNP increased, the surface tension with the mylar decreased, levelling off at about 31 dynes/cm, which is slightly above previously determined surface tensions for polyester. They concluded that it was not possible to prepare TNP solutions which will spread on polyester films. They found that there was some adsorption of TNP by both the cotton and polyester fibres which increased their surface tensions slightly. The vertical wicking of polyester increased with increased concentration of TNP, plateauing after the "critical micelle concentration". Its wicking improved with addition of NPH. The wicking of cotton was unchanged when the TNP was added to water. They concluded that if a fabric is hydrophilic, its wickability is not increased by the addition of TNP to water.

They found the drop absorbency time for the polyester to be very high and then to decrease as TNP was added to the water. The point at which the decrease plateaued out was at a higher concentration of TNP than was the case for the vertical wicking. The drop absorbency for the cotton was so short that adding TNP was pointless.

The solution retention values initially stayed the same for both fibers as the surface tension of TNP was lowered. When surface tension of TNP became less than 64 mN/m for the polyester and less than 42 mN/m for cotton, the solution retention values fell, both becoming constant again at a TNP surface tension of about 34 mN/m. They conclude that the values for cotton are higher because they represent both capillary and imbibed water. As surface tension decreases, the capillary forces are less, so more liquid will be taken away during the centrifuging. Adding NPH to the polyester increased its water retention, its wickability and its drop absorbency time. They concluded that changing the surface properties of the polyester fibers by applying a hydrophilic finish has a greater effect on the moisture-related parameters than if the polyester is left unchanged and the surface tension of the water is lowered by addition of the nonionic surfactant.

Harper et al (1976) examined the moisture-related properties of cotton-polyester blend fabrics which had been subjected to various treatments. They selected two series of fabrics. One series was a range of six broadcloths with counts of 143x73 and mass per unit area ranging from 3.9 to 4.3 oz/yd². Of the six, one was 100% cotton and five were cotton/polyester blends with polyester contents of 10, 20, 34, 50 and 68%. The second series was a range of 72x64 sheetings (4.1 to 4.2 oz/yd²) in which one was 100% cotton, four were cotton/polyester blends with polyester contents of 10, 20, 34 and 50% and a 100% polyester double knit weighing 17.8 oz/yd². They desized, scoured and bleached all the fabrics. They found the reproducibility of test results in a given series was good, but found that a comparison of similar samples from separate series at times showed inconsistencies because of the differences due to sample history. They added a selection of finishes to the fabrics.

They carried out the moisture-related tests of drop absorbency, vertical wicking, vapour and liquid transport, total absorbency and regain.

They found that the drop absorbency, wicking values and vapour and liquid moisture transport was similar for all levels of blends of untreated broadcloth fabrics. The 100% polyester knit had very low liquid transport and didn't absorb any water. Adding a cross-linking finish affected the moisture-related properties. The drop absorbency and wicking time were somewhat faster for low-level blends than for the 100% cotton, but were markedly reduced at the 32% cotton/68% polyester blend level. The liquid transport was much the same for all broadcloth fabrics except for the 32% cotton/68% polyester for which it was much slower. The authors attribute this to the reduced amount of cotton in the blend. Also, more crosslinks in the cotton suggest that where crosslinking is high or excessive, there is reduced moisture transport.

They found that moisture regain and absorbency decrease as the polyester content and the crosslinking increase. The addition of polyethylene softeners reduced wicking and absorbency markedly.

Laundrying tended to restore moisture properties and coating the surface of fibers with hydrophobic polymers almost completely eliminated the ability to wet which suggested almost complete removal of liquid-carrying properties, independent of blend. They thus viewed the addition of a hydrophobic finish as an external rather than an internal change of fibre moisture properties. When they added hydrophilic finishes, they found the wicking the same as with the control. They concluded that a chemical finish can override the influence of fiber composition with respect to moisture-related properties.

When they added hydrophilic compounds, including ethoxylated alcohols and phenols, to finishes containing hydrophobic polymers, they found that as the amount of hydrophilic compound increased, the drop absorbency time became shorter and the liquid transport markedly increased until it leveled off at about 2% concentration of the hydrophilic compound.

Further, Harper et al (1976) found that the effect of mercerization on the moisture-transport properties of crosslinked-unmercerized and mercerized blend broadcloths were similar for an individual fabric blend. It was only at 68% polyester level that the wicking time become significantly longer, drop absorbency became slower and less liquid was transported per hour. They also found total absorbency to be about the same and regain more for mercerized than unmercerized, decreasing as the polyester content in the blend increased. They concluded that mercerization does not affect the external wetting ability of cotton, but has a marked effect on internal water-absorbing capacity. From results not given in their paper, they say that a high moisture regain from a chemical finish does not translate into improved liquid water transport. But hydrophilic finishes do give improved liquid water transport, but not increased regain.

They found that liquid transport of moisture in fabric by wetting and wicking was about twenty times greater than vapour transport by evaporation. In measuring water-vapour diffusion, if water was stirred rather than being static, the rate of evaporation increased from 0.1g/h to 0.25g/h for the crosslinked broadcloths of all blends. If the tests were done at 35° instead of 21°C, the rate of evaporation increased only by 0.4 g/h. They concluded that water-vapour transport is independent of fiber content or degree of crosslinking of the cotton component of these blends.

They compared the wicking and drop-absorbency of two types of fabrics, one with a conventional finish and one with a hydrophilic component in its finish. Before testing, both were laundered with a commercial detergent. They found that the wicking and drop-absorbency times increased with increasing percentage of polyester in the conventionally-treated blends and was about 10x greater than those having the crosslinking agent only. They attributed this behaviour to the inhibition to wetting and the blocking of capillary openings due to the

polyethylene softener. Total absorbency was less in conventionally finished fabrics and was now polyester/cotton dependent. The addition of ethoxylated alcohol greatly improved liquid transport. After one wash, the liquid transport rates for all the fabrics with this finish were identical, but after ten washes, fabrics with the high polyester content transported less liquid than the high cotton-content fabrics.

After the rather tortuous methods and results, Harper et al gave the following conclusions. They suggested that there is reduced moisture transport where crosslinking is high or excessive. Coating the surface of fibers with hydrophobic polymers almost completely eliminates their ability to wet and almost completely removes their liquid-carrying properties. Since this was found to be independent of blend, the authors viewed this as an external rather than internal change of fibre moisture properties, since laundering partially restores these properties. Addition of reactive wetting agents in the finish restored these properties. They suggest that for good liquid-transport properties, one use a 50% cotton content in the blend and a 1-2% reactive wetting agent in the finish.

They found that vapour transport depends on fabric structure and is independent of fiber content, whereas total absorbency and moisture regain increase with the cotton content of the blend and are reduced by crosslinking. They considered that crosslinking changed the internal fibre structure of cotton so as to reduce its water-holding properties.

Mittal and Bhatt (1983) hydrolysed polyester fabrics to get weight losses of up to 14.8%. They found that the vertical wicking and drop absorbency was much faster for the treated fabric, but did not increase with increasing weight loss except at the greatest weight loss (14.8%) where the wicking time was slower. They explained that this was due to increased interfibre space which reduced capillary action.

Olson and Wentz (1984) hydrolyzed polyester fibers and fabrics to two different weight losses and then gave them post-treatment with acetic acid or cationic surfactants. They found the wicking rates to be low for unhydrolysed fabrics, with or without after-treatment. Hydrolysis which caused fabric weight loss significantly decreased wicking time. They suggested that the carboxylates (formed on the polyester fibre surface during hydrolysis) are blocked by the cationic surfactant and the carboxylate/surfactant complex appears to re-establish a hydrophobic surface which slows water transport through the capillaries. Wetting times decreased rapidly as the hydrolysis weight loss increased. Treating with a surfactant had no effect on the wetting times for the untreated fabric, but decreased it for the treated fabric. The moisture regain stayed about the same, below 0.5%, for all fabrics and their treatments. The moisture vapour resistance increased with weight loss due to opening of fabric.

Needles et al (1985) studied how alkali treatments affect selected properties of polyester, cotton and polyester/cotton (35/65 and 50/50)

fabrics. The fabrics were staple plain weave from Testfabrics Inc. They were treated with NaOH and dried in relaxed state. Vertical wicking and water-vapour transmission were carried out.

The untreated cotton had a rapid vertical wicking rate and the cotton fabric after slack mercerization wicked at a slightly faster rate than the untreated one. The untreated polyester fabric wicked at a much slower rate than the cotton samples. The treated polyester fabric had essentially no ability to transport water by wicking. This contradicts the findings of others. The authors rationalize this by stating that their fabrics had had a greater degree of hydrolysis and weight loss. They say that, although the alkaline hydrolysis had roughened the surface of the polyester fibers and increased their wettability, the reduction in fibre diameter has interfered with and effectively shut down capillary action within the yarns and so their wicking ability. They found the alkaline treatment had no effect on the cotton/polyester blends. They state that there was enough cotton in them to provide effective moisture transport.

They found the rate of water vapour transport through fabric covering a dish filled with water at 20°C into surroundings at 20°C and 65% RH to be similar for the untreated and treated fabrics. When the water in the dish was raised to 35°C, the treated cotton had a higher water vapour transmission, even although the slack mercerization had lowered the yarn count and decreased the air spaces between the yarns. They concluded that water vapour transport across the fabrics has little to do with the air permeability of the fabric and is more closely related to fibre type, surface modification and shrinkage caused by the base treatment.

Summary

Moisture regain is decreased when untreated cotton is treated with a crosslinking agent and is increased with the addition of hydrophilic materials. Hydrolysing cotton or cotton/polyester fabrics does not effect their moisture regain.

All cottons are highly absorbent to water. Cotton/polyester sheetings were found to be almost water-resistant, this resistance increasing with the inclusion of a cross-linking agent and decreasing when a wetting agent was added. The higher the weft count, the faster the absorbency time. The drop absorbency time for polyester was shown to be to be very high and to decrease when a surfactant was added to the water. When fabrics were hydrolysed, their wetting times decreased rapidly as the hydrolysis weight loss increased.

The decreasing order of % water absorbed was found to be untreated cotton (highest absorbency), the cotton with crosslinking, polyester/cotton, cotton with a crosslinking plus a softener, polyester and then nylon.

The saturation value decreased with increased weft count and increasing cotton content in the cotton/polyester blends. The solution of imbibition increased with increasing cotton content and was not affected by thread count.

Researchers found that 100% cotton wicked faster than polyester, with blends of the two intermediate. Adding a crosslinking agent or a hydrophobic compound decreased wicking rates and adding a wetting agent or a hydrophilic compound increased the wicking rate for polyester but not for the hydrophilic cotton. Hydrolysing/mercerizing the cotton increased its wicking rate. Some workers found that this treatment on polyester made it unwickable, while others found it made the polyester more wickable. Mercerizing had no effect on cotton/polyester blends. The wicking distance increased with weft yarn count.

YARNS AND FABRICS

De Boer (1980) studied the wettability of scoured and dried cotton fabrics and measured vertical wicking, saturation value (put a drop on fabric, after 10 min, cut out the spot and weigh), the time for the drop to disappear and an immersion test in which the samples were wetted out, the water removed under controlled conditions and the samples weighed. He used cotton poplin scoured and treated to get a wide range of properties.

He found a good linear correlation between the logarithms of time and height of rise for all fabrics. Scouring treatments had little effect on immersion values except to increase the amount of moisture picked up by the original fabric. Adding a wetting agent increases the absorption rate. He pretreated the fabric in increasing concentration of NaOH, as well as increasing drying temperatures. He found that the saturation values, the times to absorb a drop and the wicking rates increased with temperature at low concentrations of NaOH, but tended to be similar at higher concentrations of NaOH.

He concluded that, from his data, the absorption of liquid in a fabric can be characterized by the saturation value and the rate at which the liquid is absorbed. However, the saturation value may not truly be a saturation value and the immersion value would be more real. He says the drop test and vertical wicking give similar information about the rate of absorption.

Bogaty et al (1953) had observed that the use of synthetics in blends with wool increased the ease of wetting and wicking rates of resultant fabrics. They used washed serge fabrics of more or less the same number of warp and weft (about 69x58) and increased the yarn number as the synthetic content increased to keep cover about the same. They used a drop absorption test in which 0.2 ml of water is placed on the fabric surface and time for complete disappearance of liquid recorded and a wicking test, measuring the time for water to rise 2.54 cm (1") up a 2.54 cm (1") wide vertical strip.

They found that the 100% wool and up to 15% blends showed high resistance to wetting and were the slowest to wick. 100% synthetic wicked fastest and was easiest to wet, with 50 to 70% wool intermediate. They napped some of the fabrics and found that the napped fabrics took longer to absorb the drop of water.

Since surface hairiness also increases with wool content, they hypothesized that drop absorption and wicking is strongly influenced by hairiness. Further, if wicking is a capillary process, it would be expected to occur more rapidly in yarns which are aligned in an orderly fashion. In yarns which are arranged in a less orderly fashion, there would be more discontinuities and so fewer available capillaries. To prove this, they fulled a hand-woven fabric and found that wicking time increased with increased felting or increased fibre randomness. They concluded that the mechanism by which synthetic fabrics wick may be less a function of the fiber properties and may involve to a greater degree the geometry of the yarn and the degree of fiber order.

Matsukawa et al (1986) measured the height of vertical wicking after 10 minutes on a series of woven and knitted cotton and polyester fabrics. They found that the greater the twist in the yarn to a limit, the higher the water went for both the warp and the weft directions. It was explained that water was absorbed mainly through capillaries formed in the yarns and the diameter of the capillary was influenced by the amount of twist. They found that the polyester fabrics did not always have lower wicking rates than the cotton fabrics. It is noted that from the results given, there is also an inverse correlation between fabric count and the height of wicking, the lower the count, the higher the wicking.

Morris et al (1985) compared the comfort properties of three warm-up suits. Of interest here are the moisture properties of the suits. Two fabrics were similar, being warp knits with napped backs. One was a 66/34 polyester/triacetate blend and the other a 54/46 polyester/triacetate blend, the former being thinner and lighter than the latter. The third fabric was a weft knit with a cut pile face and a 70/30 acrylic/polyester blend, the acrylic being in the face and the polyester in the back. It was of similar weight and thickness as the heavier warp knit.

The polyester/triacetate blends had similar drop absorption rates and liquid and vapour transport rates. The static absorption was greater and the wicking height higher in the heavier fabric, the face wicking higher than the back. The third fabric absorbed a drop 40 times more quickly than the other two fabrics, had more static absorption and over 2 times as much liquid transport. The water vapour transport was similar. The wicking rates were similar for the face and back, and intermediate to the other fabrics.

Hollies et al (1956) examined the role of yarn roughness in capillary-type penetration. They had drawn up a theoretical equation where the $s^2 = k_s t$ and found the plot of s^2 vs t to be linear for yarns over a time of 10 minutes. (s is distance and t is time.) They varied yarn twist, fibre denier and the number of fibres in the yarn in order to obtain various capillary sizes and found that the water transport rates, corrected for differences in capillary radius, were constant for yarns made from the same fibre material. They plotted twist vs water transport rate for a 100% nylon yarn, a 70/30 wool/polyester and a 100% wool and found an increase in water transport (cm^2/sec) up to 4 twists per inch and then a decrease for all three yarns. The 100% nylon had the greatest water transport rate and the wool the least. They found that, in general, the large capillaries produce higher wicking rates.

They then measured the advancing and receding contact angles of various fibres and yarns. The advancing angles of the polyethylene, nylon, polyester and wool fibres were similar and high enough to be considered unwettable. Except for the polyester, the receding angles were considerably lower, indicating that a film of water had been left on the fibre surface. Extracting the wool with organic solvents reduced its advancing angle but not its receding angle. The yarns made from synthetic fibres had lower advancing angles than the wool yarn. They all had similar receding angles. The authors say the higher advancing angle for wool is due to its natural crimp and random distribution of fibres which results in capillary discontinuity and thus abrupt changes in water transport over the length of such a yarn. Water transport can also abruptly stop due to fibre swelling which closes up capillary spaces.

In Part II of their study, Hollies et al (1957) examine water travel in fabrics varying in fibre type and fabric construction. They measured the horizontal water transport on strips of fabrics, the water-holding capacity of these strips after draining them for 1 minute and the time to absorb a 0.2 ml drop.

(Fourt had found that the magnitude of the water-holding capacity depends almost entirely on fabric construction and for fabrics of similar construction, mainly on fabric thickness.)

Hollies et al plotted the square of the distance travelled versus time for several fabric types and found them to be straight lines,

although they did not all go through the origin. They say this is an initiation period (t_g) before which the main capillary process can occur and appears to be related to the time required for the water to penetrate the surface of the yarns and fabrics.

They found that surface wetting as measured by drop absorption and by rate curve intercept (t_g) rank the fabrics in nearly the same order. Further, in general, the time required for movement of the water 1 inch horizontally is similar in magnitude to the time required for a drop to penetrate the fabric surface. They concluded that surface wetting and water travel in the fabric interior are controlled by the same fabric properties.

They then compared the water transport rate of fabrics and of yarns taken from these fabrics and found them to be quite similar. They concluded that apparently water travel in the yarns accounted for virtually all of the motion of water in the parent fabric and so the effects of yarn twist, fibre denier and yarn size on yarn water transport rates would be evident in the water transport rates of fabrics made from these yarns. They make no mention of warp and weft directions and the fact that traditionally yarns in these two directions are dissimilar.

As other workers, they found the wool-rich blends tend to have lower transport rates than the fabrics of all synthetic or cotton fibre content, again suggesting that the random arrangement of wool fibres in these yarns was directly responsible for the low fabric-wicking rates observed.

In another study, Hollies (1953-56) compared four wool/acrylic fabrics which had similar thickness, weight and texture and contained yarns of comparable size, twist, crimp and fibre count but had different water transport rates and surface wetting times. He found the differences in these properties were due to the differences in contact angles for the yarns taken from the fabrics, the yarns having more randomly arranged fibres, having higher contact angles and being from fabrics that did not wet readily.

He concluded that it is the randomness of the arrangement of the fibres in the yarns in the fabrics which influences the amount of water carried by the fabric, the distance it travels and its wettability.

Kawase et al (1986) studied the effects of finishes on capillary spreading. They used cotton, rayon, nylon and polyester fabrics of about the same weight and porosity. The spreading liquids were distilled water, water/ethanol (1:1) and n-decane. They found in plotting spreading area versus the log of time, they got 2 slopes. One they called phase one and it is very short, between 9 and 18 s. They consider that liquid doesn't have time to diffuse into fiber. In phase two, the exponent of time (n) increases with drop size, whereas it stayed constant in phase one. Kawase says the difference between n in theory and practice is due to the

permeability of cotton to water and thus decreases effective liquid volume.

Minor et al carried out extensive wicking experiments which are reported in several papers which will be reviewed all together here. In one of their papers, (1960) they considered organic liquids in textiles, making the assumption the flow through and in the warp and weft directions is by capillary. They reduce Washburn's equation to $s^2 = k't$ and say a plot of distance² (s^2) vs time (t) should be a straight line, and if it is, then the following conditions are upheld:-

1. the physical properties of the liquid and solid remain constant throughout the system;
2. the driving forces are forces of capillary action;
3. the radius of the tube or the equivalent radius of a nontubular system is essentially constant; and
4. the supply of liquid remains adequate.

They placed nonvolatile liquids on a woollen fabric and observed that the liquid drop either failed to enter the fabric, entered the fabric but did not wick out or entered the fabric and wicked out very rapidly in all directions or in one direction.

They measured the vertical wicking rate of several liquids in nylon filament yarns and found the s^2 vs t plot to be linear, the slope varying with the liquid. As they show in a later paper, the slope is related more to viscosity than to surface tension or density, the lower the viscosity, the faster the wicking rate. Because they got a straight line, they concluded that up to 12 cm, the effect of gravity was not appreciable. To investigate the effect of gravity, they observed the wicking in a cotton yarn held in the horizontal and vertical directions. Initially they found the wicking rates to be identical until about 7 cm was reached when the vertical wicking rate became less than the horizontal one, showing, they say, the effect of gravity. This did not show up in the nylon because it had an equilibrium wicking height of 2 to 3 m.

They found the variability in vertical wicking to be greater for wool yarns than for the cotton and nylon yarns and that the cotton and wool yarns did not give good straight line plots as the nylon did.

Next they studied the transfer of liquid from yarn to yarn. Two yarns were crossed at right angles and a drop placed on one yarn slightly below the intersection. Once the liquid reached the intersection, the intersection acted as a reservoir, feeding the two yarns equally.

To examine migration in interyarn spaces, they took a twill fabric which had "ribbon-like" weft, i.e. a Saran monofilament seat cover fabric. This fabric had 3 sizes of spaces between the various yarns. They found that the liquid in the largest space moved to the second largest and on to the smallest space, finally pooling in the yarn interstices.

Next they studied the vertical wicking in sateen fabrics (they did not say what the fibre type was). For their wicks, which were 1" wide, they got the effects of gravity after 3" (7.5 cm), that is when the straight line started to become a curve. The various liquids showed identical wicking patterns on "Lebanon flannel", except that the wicking rates were different. In the case of the moderately volatile liquids, the apparent wicking rate decreased abnormally with time due to evaporation of liquid from the wick.

Finally, they looked at the transverse migration of liquids through fabrics by stacking small swatches one on top of the other and placing 2 cm of the stack in a liquid. They got the same curve as they did for vertically wicking, so concluded that there is essentially no difference between capillary migration through the thickness of the fabrics and the capillary migration in the plane of the fabric.

In their first part of a series of papers (1959A), they used nylon and viscose-rayon monofilaments, the nylon fibres having a circular cross-section and the rayon, a crenulated cross-section. The fibres were made into yarns, one with a loose twist, the other with a tight twist (4.4 and 10 turns per cm). Their vertical wicking rates were measured, using nonvolatile organic liquids. The height of rise vs. the square root of time rates were found to be linear over a distance of 12 cm, a distance they say would be unaffected by gravity, and was faster for the loosely-twisted nylon. The ratio of the equivalent capillary radii for the loose and tightly-twisted yarns was estimated to be 2 for the nylon and 1.3 for the viscose. The experimental results were in quite good agreement for the nylon but not for the viscose. They attributed this to the channels in the crenulated rayon. Diethylene glycol gave anomalous results for both fibres. They thought that this was because it is hygroscopic and this would affect the wicking rates, the wicking rate in the loose yarn being much much faster. The ratios of the equivalent capillary radii for the loose/tight, nylon/rayon were also calculated and found to be good for two liquids for the "tight" ratio. Again they explain the anomaly by the crenulated viscose.

They contend, that if a yarn is regarded as the equivalent of a capillary tube, then the wicking rate should vary directly as the surface tension of the wicking liquid and the cosine of the contact angle and inversely as the viscosity. They found reasonably good correlations between the fabrics and the yarns they tested. They suggested that in the few instances where agreement was not good, that the test liquid had swollen the fibres to decrease the wicking rates.

They studied the wicking of droplets on yarns and found that the plot of the log of time against distance to be linear until such time as the drop disappeared completely into the yarn. They also found that the liquids either wicked extensively or stopped relatively shortly after the drop disappeared into the yarn. Since wicking consists essentially of movement from large capillary spaces into smaller ones, high contact angle hysteresis inhibits this movement, and thus wicking.

They introduced 'line density', the quantity of liquid held by a unit length of yarn. With wool, the liquids of high contact angle hysteresis show a much higher line density than those liquids with low contact angle hysteresis. For a more detailed picture, they cut the yarn into suitable lengths at various stages of wicking and determined the amount of liquid in each segment. They conclude that the ultimate length of the limited reservoir region in yarns of constant radius differs from liquid to liquid and depends on the contact angle hysteresis of the fibre-liquid system, the higher the contact angle hysteresis, the shorter the contact angle hysteresis.

In the next part of their paper (1959B), the fibres they used were wool, nylon, glass, viscose and acetate rayon and the liquids non-volatile organic ones. They observed three types of behaviour. One, the drop slowly shrank and appeared to spread out over the fibre, eventually disappearing. Two, the liquid entirely surrounded the fibre and did not spread, rather forming a bead with the fibre passing through the middle as an unduloid. Third, the contact angle was very high and the drop sat on top of the yarn, described as clamshell form.

Whether a droplet forms an unduloid or a clamshell depends on the contact angle and on the volume of liquid relative to the volume per unit length of fibre. Under certain conditions, the unduloid can be manipulated into a clamshell and vice-versa, both forms being stable ones.

The effect of gravity was very small compared to the influence of surface and interfacial forces. Liquid would creep along the grooves of crenulated viscose, but not along wool fibres.

They next examined the capillary action of two parallel fibres. When the fibres were separated by the distance of about one diameter, and sufficient liquid was placed on them, the liquid would leave its elliptical form and wick out between the fibres. If the fibres were very close together, the liquid would wick out very quickly, creating a strong pressure to draw the fibres closer. This was dependent on the fibre type and liquid used, i.e. the contact angle of the two. To explain this, they give this equation to describe Figure 1:

$$\frac{dF}{ds} = \frac{d(\text{Area LA})}{ds} \cdot k_1 + \frac{d(\text{Area SL})}{ds} \cdot k_2$$

where F = the free energy of the system

$k_1 = \gamma_{LA}$ and $k_2 = (\gamma_{SL} - \gamma_{SA})$

k_2 is negative in systems where the contact angle is less than 90°

It is only in these systems that dF/ds can be negative and wicking can take place. The ratio of the magnitudes of $d(\text{Area SL})/ds$ and $d(\text{Area LA})/ds$ depends on how closely the fibres are spaced. Close spacing decreases $d(\text{Area LA})/ds$ while $d(\text{Area SL})/ds$ remains unchanged and tends to promote wicking.

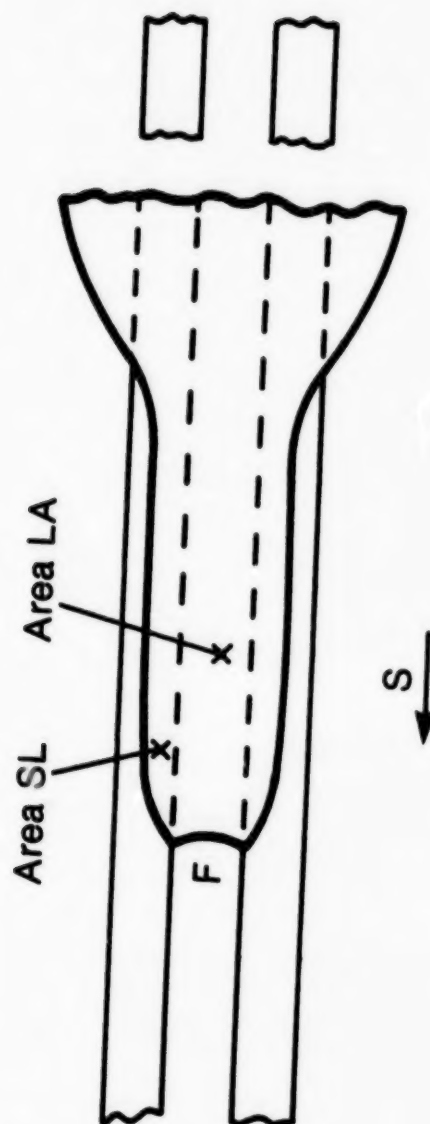


Figure 1: Illustration of Variables in Minor et al's Equation

Further, a decrease in the algebraic value of k_2 will also promote wicking since a small negative k_2 corresponds to a high equilibrium contact angle. Liquids of low contact angle will wick at a wider fiber spacing than liquids of high contact angle.

When the reservoir droplet is small, any increase in Area SL at F, the force front, causes a decrease in Area SL at H. Thus $d(\text{Area SL})/ds$ might be big enough to make dF/ds negative when R is large, but too small to make dF/ds negative when R is small. Another possibility is hysteresis, the advancing contact angle at F could be greater than the receding contact angle at H. This would tend to stop the forward motion at F when R becomes sufficiently small.

They conclude the paper with a description of how they measured contact angles of fibres.

In Part IV of their paper (1961), Minor et al say that there are several ways liquids go through fabrics - by capillary transfer or penetration, by pressure or expulsion penetration (i.e. by pressure of a weight on the fabric or by centrifugal or gravitational force) and by impact.

As they had shown, a mass of liquid in a non-uniform fibrous capillary will tend to move into the narrower capillary spaces, provided the contact angle of the system is less than 90° .

Napped fabrics have naps which act as pillars, raising the fabric off the skin. In order to have liquid transfer, the nap must be so weak and sparse that it does not effectively separate the liquid-laden yarns from the substrate (what lies under the fabric), sufficient pressure is applied to collapse the nap and allow the yarns to make contact, the pressure is sufficient to compress the nap to the point where it draws liquid out of the yarns by capillary action and brings the liquid down to the substrate or the nap fibres are crenulated and can act individually as liquid conduits.

For rapid transfer, the substrate must be wettable and contain a finer-pored system than the fabric and a system of at least as a low contact angle. It should also contact the liquid-bearing fabric above it over a relatively large area, thus affording many individual channels of transfer.

They tested capillary penetration with the mandrel test, similar to Miller's apparatus (1986), penetration by placing a weighted glass plate on the fabric and impact by throwing drops at the fabric.

They found that with capillary penetration, there is a critical pressure above which the liquid will go through the fabric and this depends on drop size and is unique for each liquid-fabric pair. The drop size has to be large enough for gravity to be an important factor before it affects capillary penetration, making penetration very rapid.

One of the most important factors affecting capillary penetration proved to be weight of liquid per unit area of wetted fabric surface which they have called surface density. It is at a maximum the moment the drop enters the fabric and decreases as the liquid spreads. Penetration is also influenced by the properties of the liquid. Liquids which wet the fabric, but fail to wick laterally, tend to penetrate extensively, particularly over long periods of time. The effect of fabric construction is predominant in determining the rate and extent of penetration. They found that the penetration rate depended on the nap on the fabric surface, the cotton sateen penetration was the fastest, wool serge next and a "jack shirting" with an abundance of wool napped fibers, a barrier to the liquids.

The pressure penetration or expulsion test was influenced by type of fabric, type of liquid, drop size, time between applying the liquid and placing the weighted glass on the wet spot (extent of wicking), weight and area of glass (expelling pressure), the time the weight was left on the spot and the nature of the underlying surface which receives the liquid.

They found that the expulsion test results resembled those of the mandrel test and that wicking time was one of the more important variables governing penetration. Increasing the time resulted in smaller transfer of liquid to the underlying surface. The degree of penetration was increased by increasing the pressure, although not linearly. Lengthening the time tended to increase the quantity of liquid transferred to the paper, especially with very viscous liquids.

They found the differences between capillary and pressure penetration to be relatively small over a wide range of fabrics and liquids. The major differences occurred when the capillary properties tended to prevent wetting and entry of the liquid into the fabric.

With the impact testing, they found that liquids of low viscosity penetrated to a greater extent than did liquids of a high viscosity, large drops penetrated the fabric more often than small drops, the weight penetration ratio varied with viscosity as well as with drop size and type of fabric, fabrics with greater cover being more resistant. For each fabric-liquid pair, there was an optimum drop size which gave the highest weight penetration ratio. Penetration due to impact took place instantly if it took place at all.

They found no correlation between impact penetration and air permeability or wicking, but a correlation with fabric cover (determined by the amount of light which shines through a fabric.)

They found that the static penetration test varied from the impact penetration test in two ways, one the quantity of liquid available for penetration is smaller than the original impinging quantity, and the area over which the impinging drop spreads is greater than the area over which the statically applied drop spreads.

They give results for a fur fabric with a knitted back and a tufted pile. The knitted back wicked extremely rapidly with the test liquid but not through the pile to the paper underneath. The pile side had no lateral wicking. The penetration into both sides was greatly influenced by surface density. Under impact, both sides showed a very high penetration ratio because of its openness.

Summary

Wool was found to be the slowest to wick, and adding synthetics to it increased the rate of wetting and wicking. Contrary to results described earlier, polyester did not always have a lower wicking rate than cotton. Randomly-oriented yarns or fabrics are slower to wick than orderly ones. The pile side of fabrics may or may not wick more than the back side of the fabric. Wicking rates are increased by adding a wetting agent, raising the temperature, using crenulated fibres and increasing the twist of yarns to a limit.

There was agreement that the wicking of a fabric is described by distance squared versus time, this relationship being a straight line until the influence of gravity comes into play at about 7 cm up the wick. It is considered that fabric construction is predominant in determining the rate and extent of penetration of a liquid. Liquid moves from large to small pores in a fabric with time.

TRANSFER FROM LAYER TO LAYER

Adler and Walsh (1984) examined the mechanisms of transient moisture transport between fabrics by soaking the fabrics in one of three solutions, water, a salt solution or a thickener solution. Treated samples were dried to a specific moisture content, then placed on top of a conditioned control sample. The samples treated with thickener or water were weighed at intervals. The control samples placed with the salt samples were measured for salt content with time. The premise was that the water would give both diffusion and wicking, the salt could only be transported in the liquid by capillary wicking or liquid transport and the thickener would be so viscous that only diffusion would occur. Unfortunately their experiment breaks down at this point. Based on either unsubstantiated or confused results, they claim that there is a critical moisture value for the onset of capillary action between fabrics because

the capillaries of the one fabric must be filled first before capillary wicking to the second fabric can occur. They say that above 30% regain, capillaries begin to fill and so the amount of moisture transported due to diffusion reaches a maximum at 30% above regain and stays constant thereafter. Further, they say there is capillary wicking, but not vapour diffusion at 122% above regain.

Spencer-Smith (1977) placed dry fabrics on wet ones, topped with a 0.3 mm glass plate to apply light pressure. The fabrics were removed at regular intervals and weighed. He found that no liquid water was transferred from the wet fabric to the dry one unless the excess regain of the wet fabric exceeded about 70 to 80%. He states that the critical regain will depend on the fabric structure and the pressure between the two fabrics. He assumes that liquid transfer occurs when there is free water on the upper surface of the lower fabric.

In the past few years, Miller at the Textile Research Institute, has carried out various experiments to examine liquid transport through fabrics. Some of the experiments are more applicable to industrial processing or superabsorbents than to clothing. Results, pertinent to clothing, are summarized here. In a study with Clark (1978A), they devised an apparatus in which a known flow is imposed and pressure changes during contact are determined. They found that when liquid first makes contact with the fabric, the pressure usually, but not always, decreases as capillary or wetting forces exert an upward pull which creates a vertical tension or negative pressure on the liquid column. If there is no appreciable attraction between the liquid and fabric surface, there is no pressure drop. There is an increase in pressure, reaching a peak when liquid breaks through fabric, then a drop to steady state. It is noted that the liquid usually breaks through at a few points, and then the liquid spreads from these to cover the upper surface of the fabric. Although the dry fabrics exhibited a wide range of wet-through resistances, these resistances all dropped to about the same value when the fabric was prewet, probably because of the surface layer of water left on the fibers after forced air drying. Under such conditions, liquid was advancing over essentially a water surface so that fiber-surface wettabilities had become about the same in all cases. The inference is that the wet-through resistances for these fabrics depend mainly on fibre-surface characteristics rather than fabric construction.

In the second part of this study, Miller and Clark (1978B) found that the wet-through resistance increases with velocity for acrylic, polyester and cotton. They considered that at low velocities, water goes through most easily-penetrated pores. At higher velocities, the water has to go through less easily-penetrated one and so high wet-through resistances are obtained.

In work done with Perkins (1986), Miller looked at liquid break-through using an apparatus which controlled barrier fabric tension, contact pressure between the layers, size of liquid drop, energetics of

liquid deposition and time of contact between layers. They used a cotton fabric and a 65/35 polyester/cotton fabric which both had the same pore size but differing wettabilities. They found that when the cotton was on top of the blend, less than 25% of the water got through to the blend. When the blend was on top of the cotton, there was about three times as much water in the cotton as there was in the blend. When the wettability remained constant and the pore size differed, it was found that 50% of the water very quickly accumulated in the lower, large-pored material and then slowly went back up onto the smaller pore fabric. When both the pore size and wettability were the same and the liquid was a surfactant solution, no reversal was observed. With water there was a reversal. They say that the reason is because, with water, a capillary pressure exists between the two layers. This is not the case with the surfactant.

Three-layer sandwich constructions in which the middle fabric is not the same as the other two, were tested to see if they would uphold the theory. When cotton was the middle layer, it accumulated almost all of the water and let very little go through to the polyester layer below it. When the polyester fabric was in the middle, some water did get through to the bottom layer. Using glycol, they found that most of it accumulated in the middle cotton layer, whether the outsides were woven or non-woven polyester or woven polypropylene. Initially, the nonwoven polypropylene did not let the glycol through to the cotton. With time, it did and the majority of the glycol accumulated there.

Finally, they studied asymmetric barriers, using two sets of cotton/polypropylene fabrics in the four permutations. The ethylene glycol penetrated through to the bottom layer (polypropylene) only when the two cotton fabrics were in the middle of the sandwich. When a surfactant was used, some of it did get through to all layers, no matter what the configuration. However, again, the most got through to the bottom layer when the two cotton layers were in the middle of the sandwich.

Miller and Perkins present some theoretical equations to describe the mechanism rather than to prove it.

Gillberg (1986) studied the penetration of a variety of liquids through fabrics using above-mentioned Miller and Perkins's apparatus. She found that the penetration was very fast with low viscosity liquids and non-existent with liquids which have contact angles greater than 60°. Further, she found that fabric construction and its wettability control liquid penetration, with the penetration decreasing with fabric thickness and, although unsubstantiated, with yarn crimp. Attempts to correlate various parameters were unfruitful.

Summary

Wicking from layer to layer is dependent on the water content of the fabric, the hydrophilic nature of the layer, the wettability of the fabric layers and on the pore size of the material. With time, the water will accumulate in the fabric with the smaller pore size. There is disagreement whether or not penetration depends on fabric construction or not.

SUMMARY AND RECOMMENDATIONS

The literature review has shown that in order for a fibre, yarn or fabric to wick, it must first wet. The dominating factor in wetting is the surface tension of the material which must be less than that of the liquid which is to wet it. A lesser factor is the amount of surface area contact between the material and the liquid, the greater the contact area, the faster it wets. Wicking likewise is surface tension dependent, this being either a property of the material itself or of a monolayer of the liquid on the material surface. The main physical property which promotes wicking appears to be the presence of well-defined channels. Absorbency is not necessarily a function of either wetting or wicking.

The review indicates that there are several factors which are not properly understood and it is recommended that they be investigated. They are as follows.

1. The work of Cassie and Baxter on the effect of wire spacing and wire diameter on wetting should be extended to see if it is applicable to textile fibres, yarns and fabrics, and if not, a theory developed which does explain their behaviour.
2. The movement of water from layer to layer has been studied to a limited extent by Spencer-Smith and poorly by Adler and Walsh, although their methodology is sound. It would be extremely informative to repeat the experiments of Adler and Walsh.
3. As an auxiliary to #2, there are available jogging suits and underwear made from doublecloths or pile fabrics in which the face is of a different fibre than the back. The question is - is there wicking from one layer or surface to another, and if so, what are the important variables.

4. The presence of capillary water is essential for the movement of gross amounts of water from one layer of fabric to another and to expedient wicking within a fabric. There has been considerable discussion as to what conditions promote the occurrence of capillary water in fabrics. Thus, some method should be devised to detect the presence of capillary water and to determine what amounts of it are necessary to promote layer-to-layer movement and in-fabric wicking.

All this work should culminate in knowledge which could be used to allow for the intelligent design of wicking or non-wicking systems for clothing.

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This paper reviews the basic theories of moisture and liquid transport. The methods used to measure liquid-substrate interaction are summarized, compared and discussed as to use. The wetting properties of fibres, yarns, fabrics, chemically-treated fibres and chemically-treated fabrics as determined by many researchers are presented, as well as the results of moisture transfer from fabric layer to fabric layer. Recommendations are proposed for areas where additional research is required on wetting properties to provide a more adequate base for the intelligent design of wicking systems for clothing.

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